R&D ACTIVITIES OF PTB IN THE FIELD OF COORDINATE METROLOGY

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Abstract: Research on coordinate metrology has been performed at PTB since the 1970s. Today the field of coordinate metrology has broaden significantly, and PTBs research activities in this area cover the measurement of micro parts up to complete aircrafts. The diversity of 3D measurement techniques addressed includes coordinate measuring machines (CMM) with tactile and optical sensors as well as instruments like measurement robots, fringe projectors, laser trackers, computer tomography instruments etc.. This metrology equipment is operated in a measurement laboratory as well as in production environment. The paper presents some selected research activities dedicated to PTB's mission to provide the base for accurate and reliably metrology in industry. The large number of cooperations with industrial partners thereby documents the economic relevance of this work for the German Industry.

1. INTRODUCTION

Coordinate metrology plays an essential role in the geometrical inspection of industrial parts. In Germany, more than 25,000 conventional co-ordinate measuring machines are currently in use. In addition, the number of other instruments for 3D metrology like measurement robots, fringe projectors, laser trackers, computer tomography instruments etc. is constantly growing. Industry aims at accurate, fast and strictly traceable metrology to control tight production processes and satisfy highest quality demands. PTB supports industry by providing artifacts and calibration services, by active research on innovative metrology and by promoting standardization on a national and international level.
Research activities are generally directed towards accuracy and traceability issues, here the PTB can capitalize on the excellent infrastructure and the continuity and experience of the staff. This is seen as a necessary prerequisite to deliver reliable state of the art metrology. In the following, some exemplary research activities are briefly presented that show the broad scope of activities in the field of coordinate metrology at PTB.

2. VIRTUAL MEASUREMENT INSTRUMENTS FOR UNCERTAINTY EVALUATION

The quality characteristic of a measurement and a necessary requirement for traceability is its uncertainty. The measurement uncertainty characterizes the estimated variation of the measured values assigned to the measurand [1]. An overestimation of the measurement uncertainty results in unnecessarily tight margins for the production process, while an underestimation may lead to the release of faulty products to the customer. Today, uncertainty statements are increasingly required for measurements in industry. The uncertainty of co-ordinate measurements is difficult to determine, due to the large number of uncertainty contributors, the dependency on the measurement strategy and the numerical computations involved in the measurement tasks. To evaluate the task specific uncertainty of coordinate measurements, PTB developed the so called *Virtual CMM* [2]. It makes use of Monte Carlo methods and accounts for the influences of the CMM, the measured part and the environment. It includes a detailed model of the geometric deviations of the CMM that also considers the thermal expansion and bending of the CMM due to deviations from the reference temperature and external temperature gradients. The Virtual CMM is embedded in a software module, that can be linked to the evaluation software of a CMM (Fig.1).
The Virtual CMM software was meanwhile integrated into the commercial software of two CMM manufacturers. In a collaborative project of PTB together with 8 competent industrial measurement laboratories the *Virtual CMM* was introduced in industry. Measurements on calibrated artifacts (with well known reference values) were used to validate the uncertainty statements calculated by the VCMM. The aim was to achieve accreditation for the traceable calibration of prismatic parts, which was achieved by 4 laboratories in 2003. Since than, more than 500 workpieces have been calibrated based on the VCMM method.
A current research projects with the three largest CMM manufacturers worldwide aims to facilitate the

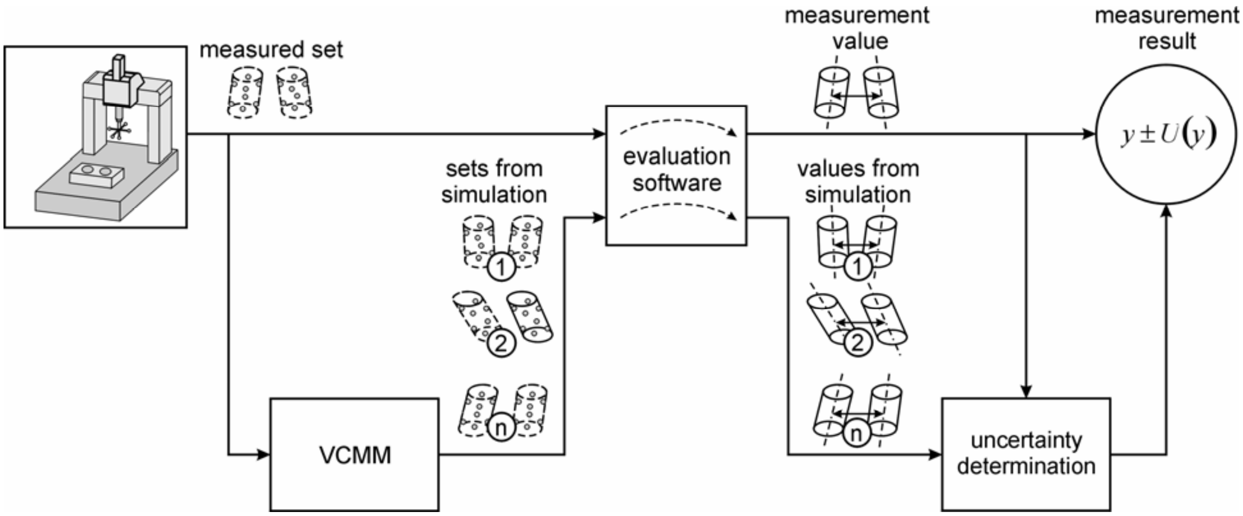

Fig. 1: *Schematic data flow of the Virtual CMM integrated in a manufacturers evaluation software.*

input parameterization of the Virtual CMM and to improve the handling of form errors of workpieces. Another project (in collaboration with 9 industrial partners, including the two largest Lasertracker manufacturers) will implement the *Virtual CMM* approach to Lasertracker measurements.

PTB regards the development of *Virtual Instruments* as one of the major challenges to improve the traceability of coordinate measurements in industry and as one of the strategic tasks also for the next years.

3. MULTILATERATION FOR CALIBRATION OF CMM AND MACHINE TOOLS

Based on the principle of multilateration a method for the spatial calibration of measuring instruments and machine tools was developed. The principle is based on the measurement of spatial distances. The method can be performed with a conventional laser tracker (LEICA, FARO etc.) or with the new developed LaserTRACER, especially designed for this application. The time needed for a full error mapping of a machine (position, straightness, squareness, pitch, yaw and roll of all axes) takes less than 4 h. The method does not require any precise adjustment or positioning of calibration tools and can be performed by a trained machine operator after short instruction time [3].

For highest precision applications of the method the dedicated LaserTRACER was developed in collaboration with the National Physical Laboratory (NPL) in the UK (Fig. 2). Unlike a commercial laser tracker, the LaserTRACER is based on a patented principle with unsurpassed accuracy of the rotation centre: A reference sphere with form errors below 50 nm is the optical reference of the interferometer [4].

Using the LaserTRACER for multilateration, calibration of CMMs and machine tools if almost any size could be demonstrated with highest accuracy: The method has been applied to the calibration of 3D micro-stages with an axis length of 25 mm up to horizontal arm machine with axis length of over 6 m.

Meanwhile the instrument and the method has been successfully commercialized by a spin-off company [5] of PTB.

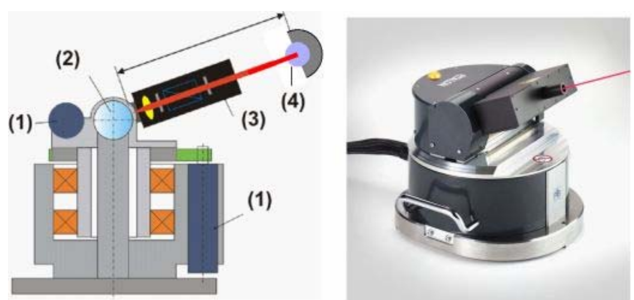

Fig. 2*: Left: The principle of the LaserTRACER (1) drives, (2) reference sphere, (3) interferometer, (4) reflector. Right: Commercial instrument [5]*

4. SIMULATION LABORATORY FOR PRODUCTION ENVIRONMENT

Coordinate metrology in a laboratory environment has reached a remarkable level of accuracy. Calibration laboratories and industrial users have done significant investments in measurement labs to achieve a high temperature stability and a low level of ground vibration. But for economic reasons metrology increasingly moves close to the production line to realize fast control loops for the production. As a consequence, the next generation of measurement instruments has to deliver laboratory precision under production environment.

PTB will support this development by erecting a simulation lab for production environment, where the influences of thermal gradients in time and space as well as vibration and airborne sound on measurement processes can be studied (Fig. 3).

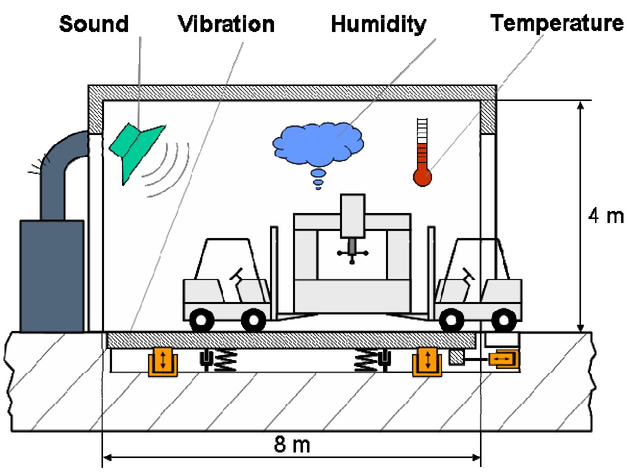

Fig. 3: *Scheme of the simulation lab for production environment*

The laboratory is planed to realize temperature changes of up to 10 K/h in a range between 15-30°C and 3 axis floor vibration in a frequency range between 1-80 Hz. A set of mobile heat pumps will be developed to generate changing spatial gradients. The simulation lab will be usable for measuring machines up to 15 tons, two large doors will make to loading and unloading procedure simple to be able to analyze machines of different types and manufacturers. An consortium of partners from industry and academia supports the PTB in the planning. The laboratory will be in operation in 2008. With the new simulation facility, better models for the influence of the environment will be developed and instrument manufacturers will be supported in reducing the sensitivity of their instruments to environmental influences.

5. THE TACTILE-OPTICAL PROBE

The growing number of component parts with very small functional features leads to a demand for measuring instruments that provide full 3D measurement capability for different structures with dimensions clearly below 1 mm. By tactile probing, the mechanical functional properties are measured directly and in many cases the traceability of the result is superior compared with optical measurements. The tactile-optical microprobe developed at PTB combines both the advantages of tactile probing and the accurate optical measurement of the probe deflection [6]. The setup of the microprobe system consists of a bended optical glass fiber with a small probing sphere attached to its end. The glass sphere diameter can range between 10 and 100 µm and the contact forces are in the order of 1-10 µN. The probing sphere is arranged in the focal plane of an imaging system and it is illuminated through the optical fiber by a LED. Thus a bright circular disk is observed when images are acquired with the integrated CCD-camera. The basic principle of the tactile-optical probe is shown in Figure 4. Probe deflections caused by contacting a workpiece result in a detectable 2D-displacement that can be measured by image processing methods and evaluated in analogy to a conventional probing system. The tactile-optical probing system can deliver accuracies clearly in the sub-micron range for 2D measurements. The system has been commercialized very successfully by a German CMM manufacturer [7].

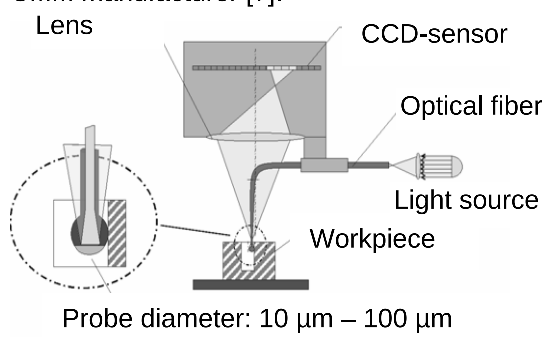

Fig. 4: *Principle of the tactile-optical probe*

Meanwhile, the system has been extended to scan in 2D. At PTB, it has been adapted also for roundness scanning of small parts. Figure 5 shows a comparison with a conventional roundness tester.

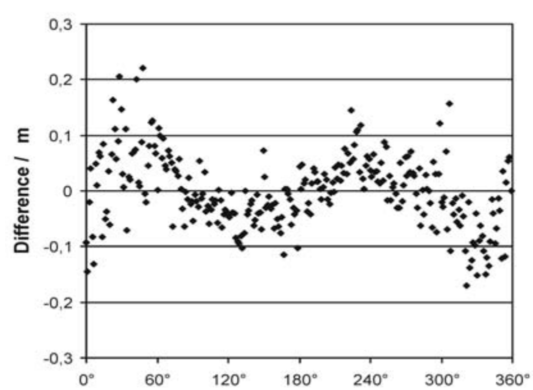

Fig. 5: *Roundness scanning with the tactile-optical microprobe in comparison with a conventional high roundness measurement machine*

However, the present mode of operation is insensitive to any out-of-plane displacements of the probing element. Currently, PTB develops a novel principle for the 3D detection of the probe deflection, that combines a simple mechanical setup with a high potential to realize an accurate and robust 3D probing system for micro parts. If a laser diode is used as a coherent light source instead, the observed image shows a distinctive speckle pattern that is generated by the varying length of the optical path within the multimode fiber and the probing element.
When changing the distance of the light emitting probing element to the camera, the out-of-plane displacements lead to a nearly radial scaling of the speckle pattern according to the numerical aperture of the imaging system. Thereby the contrast of the speckles remain almost unchanged, only the intensity changes due to the increasing distance of the light emitting sphere from the focal plane. Figure 6 shows a 3D visualization of a recorded image sequence while gradually changing the distance between the probing element and the camera.

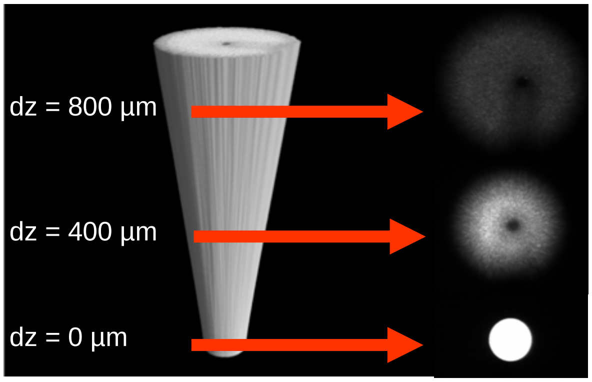

Fig. 6: *Visualization of the speckle pattern scaling effect when the light emitting sphere is defocused out of the focal plane.*

As a consequence, spatial 3D information of the probing element in relation to the camera can be principally derived from a single image: x- and y-displacement by observing the shift of the whole speckle pattern, z-displacement by evaluating its shape. The measurement of a calibrated sphere with a diameter of 25 mm firstly demonstrated the current capability of the speckle correlation method to measure in full 3D. The maximum deviations from the best-fit sphere range between -1.5 µm and 1,5 µm [8]. Further significant improvements are expected due to more sophisticated calibration strategies and refined mechanical design of the probe.

6. INDUSTRIAL X-RAY TOMOGRAPHY

Since 2001 the PTB investigates the metrological characteristics of industrial computed tomography (CT) systems for dimensional measurements. CT using x-rays, originally developed 30 years ago for medical diagnosis, has meanwhile become an important tool for industrial applications. Initially used in industry solely for non-destructive defect analysis CT is increasingly used for dimensional measurements. It is the only method to measure the inner and outer structure of objects in a non-destructive way and with high data density.
The design of industrial CT systems differs significantly from medical systems. In almost all industrial systems the object (part) is rotated on a rotary table and the x-ray source and the detector are stationary. Currently two different types of industrial CT systems are in use: so called 2D-CT systems utilizing a fan beam and a line detector, whereas 3D-CT systems operate with a cone beam and an area detector. Both types yield full 3D density information of the part. The resolution of a CT is expressed by the voxel size, a measured cubic volume element. Large CT systems with x-ray tubes up to 450 kV acceleration voltage can penetrate up to 300 mm aluminum and deliver spatial resolutions down to $(250\ \mu m)^3$. CT systems with micro- or nano-focus x-ray tubes (usually up to 225 kV) can yield spatial resolutions down to the order of $(2\ \mu m)^3$ and penetrate a maximum of 20-30 mm in aluminum.
Together with industrial partners, PTB develops procedures to improve the accuracy and the traceability of CT measurements [9] by the correction of systematic deviations, the development of interim checks and the implementation of experimental methods to determine the task-specific measurement uncertainty.
Systematic deviation have been reduced significantly by the combined measurement of calibrated reference artifacts with the part to be investigated. Thereby, deviations can be determined and corrected in further steps of data evaluation. Interim checks of CT facilities for dimensional measurements have been implemented analogous to standards and guidelines for conventional coordinate measuring machines (DIN EN ISO 10360, VDI/VDE 2617). Calibrated reference artifacts are used here. Even more as for other coordinate measuring instruments, the uncertainty of CT measurements is highly task specific. PTB investigated the applicability of the "*Uncertainty determination with calibrated artifacts"* (ISO/TS 15530-3)*, a* concept used in coordinate metrology.

With the procedures developed, task-specific measurement uncertainties (single-point uncertainty of the part surface), for aluminum casting parts measured by 2D-CT, smaller than the voxel size of the measurement have been proven. For 3D micro-CT the characterization of influence quantities, as well as further reduction of measurement deviation is object of investigation. Together with industrial partners the determination of the task specific measurement uncertainty for smaller parts is currently in progress (Figure 7).

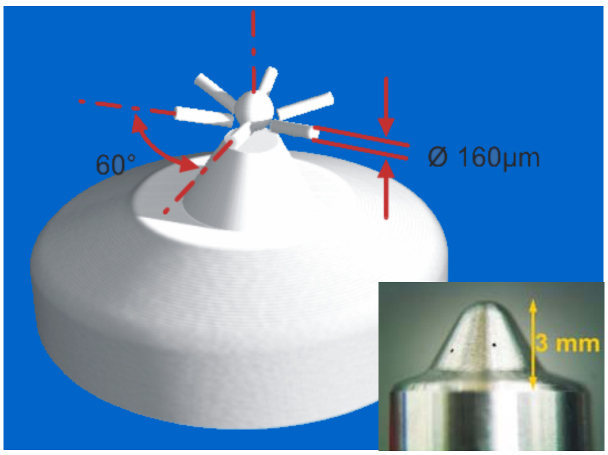

Fig. 7: Application of 3D micro-CT for the measurement of the inner structure of a fuel injector.

7. CONCLUSION

Some selected research activities of the coordinate metrology department of PTB have been presented. They document the mission of the department to support industry in the development and application of metrology, that is focused on the need of a modern production. The future needs for precision engineering in general and coordinate metrology in particular can summarized by “more accurate, faster, smaller and closer to production”. That means: reduced measurement uncertainties, shorter measuring time, increased information content, excessive miniaturization of both the measurement instrumentation and the objects to be measured and last but not least production integrated metrology to directly control production processes. These partly conflicting requirements will influence PTB’s future work in the area of coordinate metrology.

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